The role of diurnal cycle in subduction/obduction

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Abstract

The annual subduction/obduction rate can be calculated in Lagrangian and Eulerian coordinates. In previous studies such calculations were primarily focused on the case with the seasonal cycle only. By extending these calculations to the case including the diurnal cycle of mixed layer depth, the annual subduction/obduction rate can be greatly increased.

Key Words: diurnal cycle, subduction, obduction

1. Introduction

Subduction/obduction rate diagnostics is a widely used tool for the description of processes that couple the dynamics of the mixed layer and the ocean interior. This paper is concerned with uncertainties that influence such calculations.

Motions in the mixed layer have a broad spectrum in space and time; there are two prominent cycles: the diurnal cycle and the seasonal cycle. An example of the seasonal modulation of the diurnal variation of the mixed layer depth in the North Atlantic (41°N, 27°W), which was calculated from the monthly-mean surface meteorology of Bunker and Worthington (1976), is shown in the left panel in Fig. 1 (taken from Woods and Barkmann, 1986). The amplitude of the diurnal cycle of mixed layer depth reaches the annual maximum around March 1st, when the daily heat input from the sun first exceeds the surface heat loss. The amplitude of the diurnal cycle of mixed layer depth diminishes in autumn, when the heat loss to the atmosphere becomes larger than the heat gain.

Many dynamical processes in the mixed layer, such as the mixed layer deepening/shoaling and the corresponding seasonal and diurnal cycles, play the most critical roles in watermass formation (Woods, 1985). It can be seen from Fig. 1 (left) that the diurnal cycle is an important component of the mixed layer deepening/shoaling process; thus, including this cycle should be very important for the accurate calculation of subduction/obduction. In spite of the potentially important contribution it may have in the watermass formation/erosion, however, the diurnal cycle of the mixed layer depth was omitted in most previous studies (e.g., Qiu and

Huang, 1995; Karstensen and Quadfasel, 2002; Qu et al., 2002; Qu and Chen, 2009).

The reason of omitting the daily cycle of mixed layer in subduction/obduction may be twofold. First, there is no data including daily cycle with basin-wide coverage available currently. Second, for simplicity most previous calculations have been focused on the case with the seasonal cycle only. In this study, we will explore the important role of diurnal cycle of the mixed layer depth in setting the subduction/obduction rate.

2. The conceptual model

A sketch illustrating the watermass formation/erosion for the case including the diurnal cycle is shown in Fig. 2A. The upper ocean can be divided into five layers: the Ekman layer, the mixed layer, the diurnal pycnocline, the seasonal pycnocline and the permanent pycnocline. The diurnal pycnocline is very thin or vanishes at night; the seasonal pycnocline also vanishes in winter. The density structure in the upper ocean changes continuously. The two extreme states of stratification for a given station are shown in Fig. 2B: One corresponds to a state with a minimal mixed layer depth when both the diurnal and seasonal pycnocline exist, and the other a state with a maximal mixed layer depth when the diurnal and seasonal pycnocline disappear. However, in this idealized picture the permanent pycnocline is unaffected by definition.

For the case including the diurnal cycle, the annual mean subduction is defined as the annual volume flux from the mixed layer to the permanent pycnocline, passing through the diurnal and seasonal pycnocline, and the annual mean obduction is the annual volume flux from the permanent pycnocline to the mixed layer, passing through the seasonal pycnocline and diurnal pycnocline.

The seasonal modulation of the diurnal cycle in the mixed layer can be separated into two phases, detrainment and entrainment, which indicate the volume flux across the base of the mixed layer. However, similar to the case discussed by Qiu and Huang (1995), although mixed layer detrainment takes place over a substantial portion of the diurnal cycle in each day, only a fraction of this detrained water, as indicated by the lower trajectories in the upper right panel of Fig.1, can eventually enter the permanent pycnocline; thus, it is classified as effective detrainment. During the rest of the detrainment period, water parcels detrained from the mixed layer enter the diurnal and seasonal pycnocline; however, they are eventually re-entrained into the mixed layer due to the rapid mixed layer deepening downstream, as indicated by the top trajectories in the upper right panel of Fig.1; thus, it is ineffective detrainment, which does not contribute to the exchange between the mixed layer and the permanent pycnocline.

Obduction is closely related to mixed layer entrainment. During each diurnal cycle, entrainment/detrainment takes place alternately. As for the case of detrainment, entrainment in a diurnal cycle can also be divided into two phases: effective entrainment and ineffective entrainment. Obduction is the result of effective entrainment, indicated by the lower trajectories in the right lower panel of Fig.1, which occurs only during a part of the entrainment period. During the rest of the entrainment period, water entrained into the mixed layer does not come from the permanent pycnocline; instead, it may be the water previously detrained out of the mixed layer, as indicated by the top trajectories in the right lower panel of Fig.1; thus, it is ineffective and does not contribute to the annual mean obduction.

3. The subduction/obduction rate

For the case including the diurnal cycle, the annual subduction/obduction rate at a given station in Eulerian coordinates can be defined as the sum of daily effective detrainment/entrainment at this station:

$$S_E = \frac{1}{T}\sum_{n=1}^{365}\int_{T_{ns}^{ed}}^{T_{ne}^{ed}} D dt , \tag{1a}$$

$$O_E = -\frac{1}{T}\sum_{n=1}^{365}\int_{T_{ns}^{ee}}^{T_{ne}^{ee}} D dt , \tag{1b}$$

where $D = -(w_{mb} + \mathrm{u}_{mb} \cdot \nabla h_m + \frac{\partial h_m}{\partial t})$ is the instantaneous detrainment rate (De Szoeke, 1980; Cushman-Roisin, 1987), w_{mb} and u_{mb} are the vertical and horizontal velocity at the base of the mixed layer; and h_m is the mixed layer depth. T_{ns}^{ed} (T_{ns}^{ee}) and T_{ne}^{ed} (T_{ne}^{ee}) is the starting and ending time of effective detrainment (entrainment) on the n$^{\text{th}}$ day in one year.

The subduction/obduction rate for the case including the diurnal cycle can also be calculated in Lagrangian coordinates along the first/last effective detrainment/entrainment trajectory:

$$S_L = -\overline{w}_{tr} + \frac{1}{T}(h_{m,0} - h_{m,1}) , \tag{2a}$$

$$O_L = \overline{w}_{tr} + \frac{1}{T}(h_{m,0} - h_{m,-1}) , \tag{2b}$$

where $\overline{w}_{tr}$ is the vertical velocity averaged over the one-year trajectory, $h_{m,0}$ and

$h_{m,1}$ ($h_{m,-1}$) denote the mixed layer depths along the trajectory in the first and second (last) winter.

As an example, subduction/obduction rate based on the above definitions is calculated for an idealized model ocean. The model was set for the northern part of a subtropical basin. In modern terminology, within the subtropical gyre a water mass is formed at the sea surface, and it is pushed downward into the thermocline by Ekman pumping. Afterward, it downwells along isopycnals, continuing its equatorward motion induced by Sverdrup dynamics. For simplicity, however, our discussion here is focused on the idealized case of a two-dimensional flow within the meridional plane.

In our idealized model ocean, the mixed layer depth is assumed to vary linearly with the latitude,

$$h_{\max}(y,t) = h_{\max,0}(t) + k_{\max}(t)(y - y_0) \tag{3a}$$

$$h_{\min}(y,t) = h_{\min,0}(t) + k_{\min}(t)(y - y_0) \tag{3b}$$

where $h_{\max,0}(t)$ and $h_{\min,0}(t)$ are the seasonal cycle of the diurnal maximal and minimal mixed layer depth at a given station; $k_{\max}(t)$ and $k_{\min}(t)$ the slope of the diurnal maximal and minimal mixed layer depth, which were set as following: For the daily maximal mixed layer depth (h_{max}), it was assumed to be maximal at 60^{th} day and minimal 200^{th} day in one year, the seasonal variation can be seen in the upper panel of Fig.3; and at 40°N, the maximum is set at 160*m* and the minimum 37.5*m*, and then at 10°N, the maximum is set at 40*m* and minimum 22.5*m*; finally, the mixed layer depth is assumed to vary linearly with the latitude for simplicity. According to Woods and

Barkmann (1986), the amplitude of diurnal cycle diminishes in autumn. In this study, the amplitude is assumed to diminish at 280th day; moreover, the daily minimal mixed layer depth is assumed to be minimal at 200th day, as shown in the lower panel of Fig.3. The diurnal cycle of the mixed layer depth is set as a simple sinusoidal function of time: the mixed layer depth reaches the maximum at 0600 hours and the minimum at 1800 hours.

Furthermore, the velocities (vertical and horizontal velocity) are assumed to be constant in the idealized model ocean. In the case of subduction which mainly takes place in a subtropical basin, where the water is pushed into the thermocline through Ekman pumping and then continued equatorward motion, the vertical velocity (w_{mb}) is negative (downward), and horizontal velocity (v_{mb}) is also negative (southward); thus, it was set as $w_{mb} = -7.93 \times 10^{-7} m/s$ (-25 *m/yr*) and $v_{mb} = -5 \times 10^{-2} m/s$.

The annual subduction rate at station A (38°N) in Lagrangian coordinates is 88.1 *m/yr*. In Eulerian coordinates, it can be seen that only a small part of the detrainment period each day actually contributes to the effective detrainment, and thus contributes to the annual mean subduction, as shown in Fig. 4b (the daily duration of effective detrainment) and 4c (daily contribution to subduction). The effective detrainment only takes place for less than one hour each day from 54th day to 120th day in the year, the average daily contribution during this period is 1.22 *m/yr*, and the annual mean subduction rate is 81.9 *m/yr*. That is, even if the diurnal cycle of the mixed layer depth is taken into account, subduction still takes place from late winter to early spring, in consistent with the Stommel Demon (Stommel, 1979) that the subsurface ocean selects only the late winter as the window for the actual subduction into the permanent pycnocline. However, it only occurs for a short period of time each day. Moreover, the average amount of daily detrainment during this period is more than 60 *m/yr* due to the rapid shoaling of mixed layer; thus, it seems that only a very small fraction of detrainment actually contributes to subduction.

If the diurnal cycle of the mixed layer depth is omitted and replaced by the daily mean, the corresponding annual mean subduction rate is 66.6*m/yr* in Lagrangian coordinates and 62.5 *m/yr* in Eulerian coordinates. In this case, the effective detrainment is from 45th to 127th day and the daily contribution to the annual mean subduction, with the daily mean of approximately 0.79 *m/yr*, is actually smaller than that for the case including the diurnal cycle. In summary, explicitly including the diurnal cycle of the mixed layer depth can substantially enhance the annual mean subduction rate: it increases 31% in Eulerian coordinates and 32.3% in Lagrangian coordinates for this case.

Better information related to the annual mean subduction rate, timing of the effective subduction, temperature and the concentration of oxygen and other tracers at that time can make the estimate of transfer of heat, dissolved oxygen and other tracers to the permanent pycnocline more accurate. Temperature in the surface of the ocean has a prominent diurnal cycle, and it has been investigated in many studies (e.g., Cornillon and Stramma, 1985; Price et al., 1986; Webster et al., 1996; Stuart-Menteth et al., 2003); similarly, the concentration of oxygen and other tracers also have diurnal cycle. As an example, we use data collected through the SMILE (The Shelf Mixed

Layer Experiment; 38°40´N, 123°30´W) obtained from the Woods Hole Oceanographic Institution (WHOI) upper ocean mooring data archive. The average of daily mean mixed layer temperature during the period March-to-April is 10.8°*C* and the amplitude of the diurnal variation is 0.8°*C*. Similar to the mixed layer depth, the diurnal variation of the mixed layer temperature is set to be a simple sinusoidal function of time: the mixed layer temperature reaches the minimum at 0600 hours and maximum at 1800 hours (Fig. 5a). Oxygen concentration is a relative measure of the amount of oxygen (O_2) dissolved in the water, which varies with temperature and salinity. The oxygen concentration is estimated based upon the empirical equations (Weiss 1970), Fig. 5b. For simplicity, the salinity is assumed to be constant (35*g/kg*).

As discussed above, in Eulerian coordinates the effective detrainment occurs over a short period of less than one hour each day, during which the mixed layer temperature reaches the minimum and oxygen concentration the maximum (10.4°*C* and 8.94*mg/L* for the case shown in Fig. 5). Furthermore, the average of daily mean mixed layer temperature and oxygen concentration is 10.8°*C* and 8.86*mg/L*.

Take the dissolved oxygen for example, the annual estimate for the case including the diurnal cycle (derived by the annual subduction rate multiplied the maximal oxygen concentration) is 32.3% larger than that for the case with the seasonal cycle only (derived by the annual subduction rate from a model without the diurnal cycle multiplied by the mean oxygen concentration). The increase of dissolved oxygen transport to the permanent pycnocline is primarily due to the enhancement of the subduction rate associated with the explicit inclusion of the diurnal cycle, plus a minor enhancement due to the high oxygen solubility at lower temperature during the evening when effective detrainment takes place. In the same way, including the diurnal cycle can alter the estimate of transportation of other tracers into the permanent pycnocline accordingly.

It is worthwhile to emphasize that the amplitudes of diurnal cycle of temperature and other tracers at the site of SMILE are relatively small because this station is located at low latitudes. It is speculated that the corresponding diurnal cycles of temperature and dissolved oxygen concentration can be much larger for stations at higher latitudes in the subtropical gyre; thus, the transportation of dissolved oxygen, heat and other tracers may be noticeably enhanced during the evening hours when the effective detrainment takes place.

Similarly, the diurnal cycle of the mixed layer depth can also affect the annual obduction rate. Obduction mainly takes place in the subpolar gyre, where the water moving northward can be pulled into the mixed layer by Ekman upwelling; thus, the vertical velocity and horizontal velocity are positive. In our study, we set their values as $w_{mb} = 5.07 \times 10^{-7} m/s$ (16 *m/yr*), $v_{mb} = 5 \times 10^{-2} m/s$. The annual mean obduction rate at station B (50°N) in Lagrangian coordinates is 79.1*m/yr* according to Eq. (2b). In Eulerian coordinates, it can also be seen that although entrainment occurs over half of the time within each diurnal cycle, only a small part of entrainment rate in each day contributes to the annual mean obduction. In this case, the duration of effective entrainment each day is shown in Fig. 4e, and the daily contribution to obduction is shown in Fig. 4f. The annual mean obduction rate at station B in the Eulerian coordinates is 82.6*m/yr*.

If we omit the diurnal cycle and set the seasonal cycle of the mixed layer depth the same as the seasonal variation of the daily mean, the annual mean obduction rate at station B is 56.9*m/yr* in Lagrangian coordinates and 55.5*m/yr* in Eulerian coordinates. That is, including the diurnal cycle enhance the obduction rate 39% in Lagrangian coordinates and 48.8% in Eulerian coordinates for this case.

According to the discussion above, the diurnal cycle plays an important role in subduction/obduction; thus, in order to calculate the subduction/obduction rate accurately, it is desirable to include the information of diurnal cycle in our subduction/obduction model.

4. Conclusion

Our analysis based on an idealized example showed that the diurnal cycle of the mixed layer depth plays an important role in setting the subduction/obduction rate. By including the diurnal cycle in the mixed layer, the annual subduction/obduction rate can increase on the order of 30%. We speculate that difference in the daily cycle for the different parts of the basin may manifest in many ways. However, up till now, no basin-wide detailed information of the diurnal cycle in the mixed layer is commonly available through either numerical models or in-situ observations. We hope this study will stimulate further interest in examining the significant role of the diurnal cycle in watermass formation/erosion.

Acknowledgments

LLL and FW were supported by National Natural Science Foundation of China under Grant 40906007 and 40890150.

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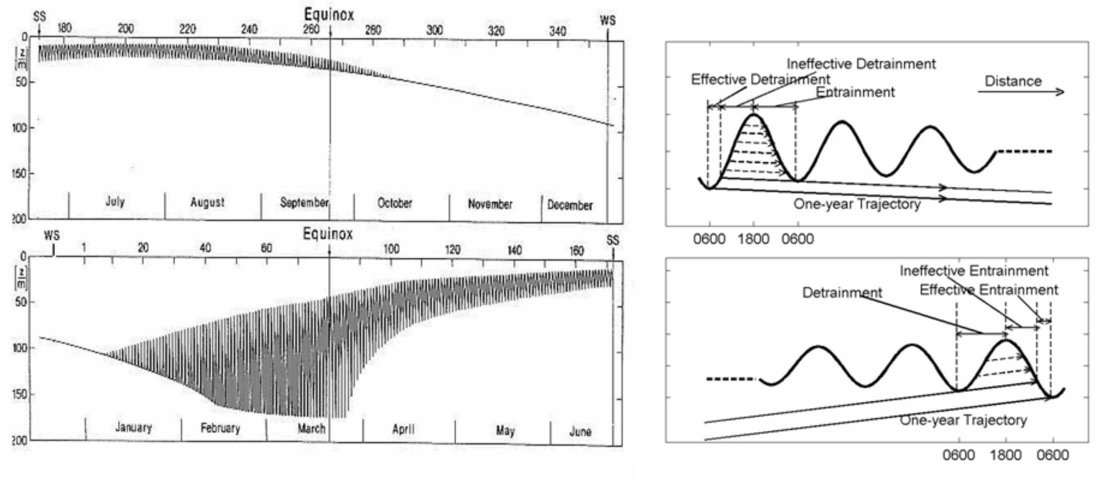

Figure 1. Left panels: Climatological seasonal-mean modulation of the diurnal cycle of mixed layer depth at 41°N, 27°W (taken from Woods and Barkmann, 1986). Right panels: the conceptual model of subduction (upper right) and obduction (lower right) for the cases including the diurnal cycle. The heavy black curves indicate the instantaneous position of the mixed layer base and the slightly slanted horizontal arrows denote the trajectories of water parcels released from (entering into) the base of the mixed layer. Abscissa denotes both time and meridional position of the water parcel released from (entering into) the base of the mixed layer.

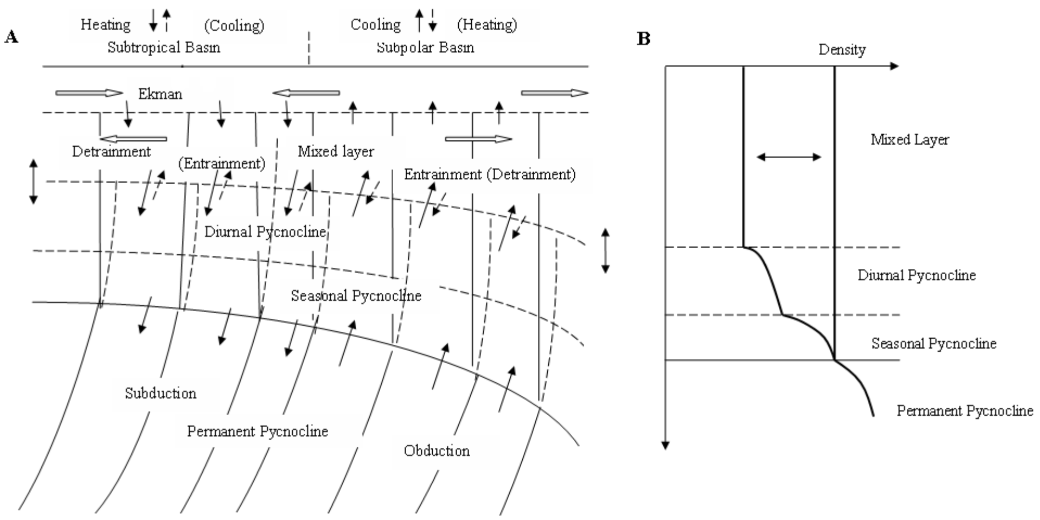

Figure 2. A) A sketch illustrating dynamics structure and processes associated with watermass formation/erosion in the upper ocean; B) Density structure for a given station: the diurnal pycnocline lies between the base of mixed layer and the top of the seasonal pycnocline which extends down to the top pf the permanent pycnocline.

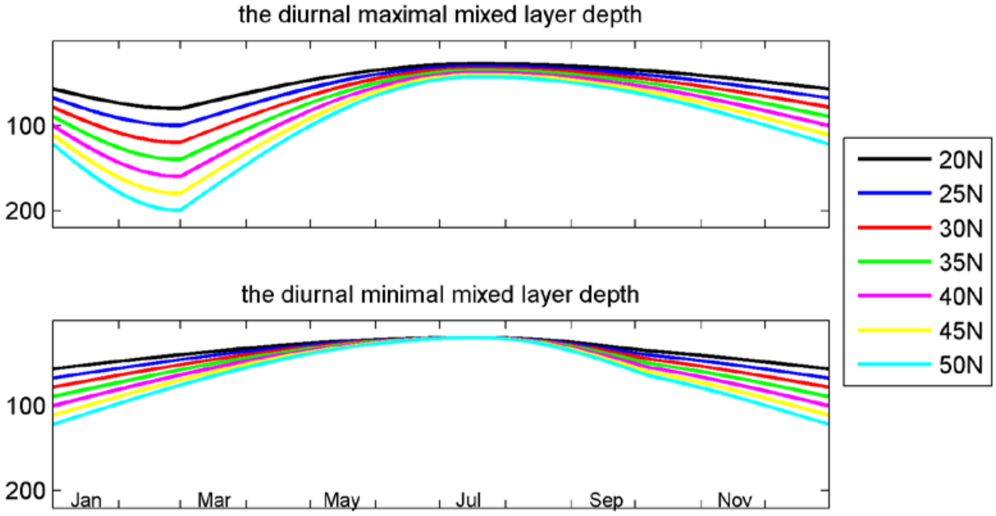

Figure 3. The daily maximal (hmax), minimal (hmin) mixed layer depth at different stations, in *m*;

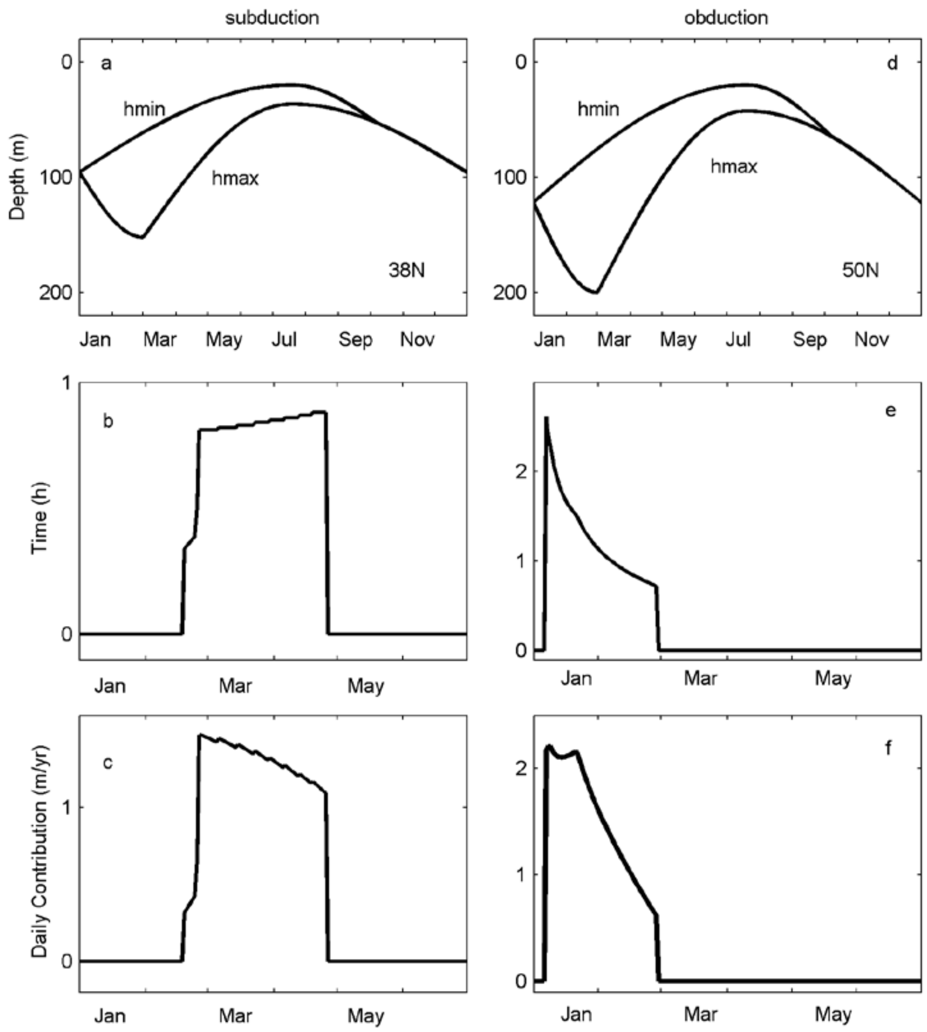

Figure 4. The daily maximal (hmax), minimal (hmin) mixed layer depth at the station 38°N (a) and 50°N (d), in *m*; b). the duration of daily effective detrainment for the cases including the diurnal cycle at 38°N, in *hour*; c) the accumulated daily effective detrainment at 38°N, in *m/yr*; e) the duration of effective entrainment at 50°N, in *hour*; f) the accumulated daily effective entrainment at 50°N, in *m/yr*.

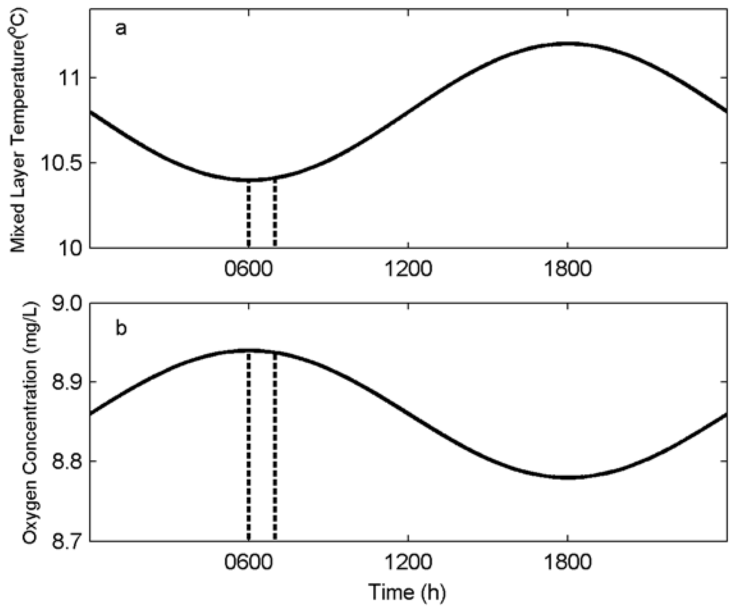

Figure 5. The diurnal variation of the mixed layer temperature in a day from SMILE data (upper panel); the diurnal variation of the oxygen concentration in a day, calculated based upon the empirical equation (lower panel).